An almost elementary Higgs
+ a few thoughts

Daniele Barducci

w/ De Curtis, Redi and Tesi - 1805.12578

Two directions should be pursued

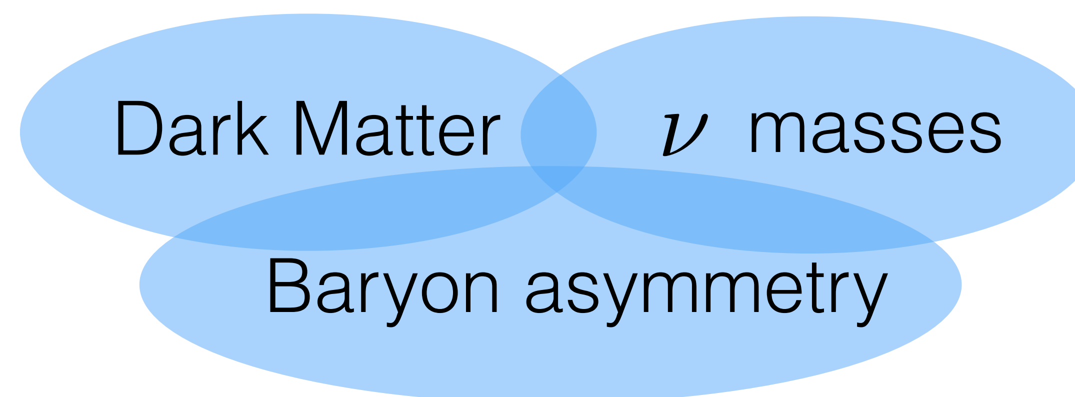
LHC is sensitive to TeV scale NP with $\mathcal{O}(0.01 - 1)$ couplings

Natural New Physics is being tested

Effective Field Theory can provide indirect reach to higher NP scales

Keep exploring this path

Relax the naturalness criteria and focus on evidences



Look for NP not related to δm_H^2

This talk

$$\frac{\delta m_H^2}{m_H^2} \gg 1$$

$$\theta G^{\mu\nu,a}\tilde{G}^a_{\mu\nu}, \quad \theta \ll 1$$

$$\frac{m_\tau}{m_{top}} \ll 1$$

$$\Omega_{\rm DM} h^2 \sim 0.1$$

$$m_\nu \neq 0$$

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}$$

Theories of Vector-Like Confinement

Strongly coupled extensions of the SM that **do not break** EW symmetry

The Higgs mass is fine tuned!

- Vector-Like fermions charged under $\mathcal{G}_{\rm SM}$ and $\mathcal{G}_{\rm NP}$

- $\mathcal{G}_{\rm NP} \sim SU(N),\ SO(N),\ Sp(N)$ interaction that confines at a scale Λ

Bounds states of the new strong interaction are formed

Theories of Vector-Like Confinement

$\mathcal{L}_{\rm UV}$ contains
- kinetic terms for new gauge and fermion fields
- interactions among the fermions

$$\mathcal{L}_{\rm mix} \sim m_{\psi_1}\psi_1^c\psi_1 + m_{\psi_2}\psi_2^c\psi_2 + yH\psi_1\psi_2^c$$

Mixing with the Higgs can be present depending on ψ SM quantum numbers

This mixing has has strong implications for VLC phenomenology

Spectrum of the theory

pNGBs from chiral breaking: $\tilde{\pi}$

Bounds states: $\tilde{\rho}\,,\tilde{\phi}\,,\tilde{B}$

Cut-off: $\Lambda \sim 4\pi f_{\tilde{\pi}}$

Theories of Vector-Like Confinement

$$\mathcal{L}_{\rm mix} \sim m_{\psi_1} \psi_1^c \psi_1 + m_{\psi_2} \psi_2^c \psi_2$$

Accidental symmetries of the UV Lagrangian

i) $\psi_i \to \exp{(i\alpha_i)}\psi_i$ dark species number conservation

Theories of Vector-Like Confinement

$$\mathcal{L}_{\rm mix} \sim m_{\psi_1}\psi_1^c\psi_1 + m_{\psi_2}\psi_2^c\psi_2 + yH\psi_1\psi_2^c$$

Accidental symmetries of the UV Lagrangian

~~i) $\psi_i \to \exp{(i\alpha_i)}\psi_i$ dark species number conservation~~

ii) $\psi_i \to \exp{(i\alpha)}\psi_i$ dark baryon number conservation

Theories of Vector-Like Confinement

$$\mathcal{L}_{\rm mix} \sim m_{\psi_1}\psi_1^c\psi_1 + m_{\psi_2}\psi_2^c\psi_2 + yH\psi_1\psi_2^c$$

Accidental symmetries of the UV Lagrangian

i) $\psi_i \to \exp(i\alpha_i)\psi_i$ dark species number conservation if $y=0$

ii) $\psi_i \to \exp(i\alpha)\psi_i$ dark baryon number conservation

- **Dark Baryon number** conservation leads to the stability of the lightest techni-baryon, as for the proton in the SM
- **Dark Species number** leads to the stability of techni-mesons made of 2 different species: this symmetry is broken by Yukawa interactions.

Both bounds states can be Dark Matter candidate. [Antipin et al. 1503.08749]

Theories of Vector-Like Confinement

Techni-hadrons at ~ TeV to be the full observed Dark Matter

Other resonances expected at the same scale, i.e. within the LHC reach

- What kind of phenomenology do we expect?
- What can the LHC say on these type of theories?

For concreteness

- $SU(N)$ gauge theories with $\square$ VLFs
- VLFs charged only under $\mathcal{G}_{\text{EW}}$ Colored guys heavily discussed at F^{750} time
- VLFs representations that appear in $SU(5)$ GUTs

$$N = (n,1)_0\,, \qquad L = (n,2)_{-\frac{1}{2}}\,, \qquad V = (n,3)_0$$

~ Bino ~ Higgsino ~ Wino

Theories of Vector-Like Confinement

$$\mathscr{L}_{\text{mix}} = y_N H L N^c + \tilde{y}_N H^\dagger L^c N + y_V H L V^c + \tilde{y}_V H^\dagger L^c V + m_V V V^c + m_L L L^c + m_N N N^c + h.c.$$

Scenario with $m_\psi < \Lambda$: QCD like chiral dynamic

[For the complementary regimes see 1707.05380]

A set of pNGBs is delivered

$$\begin{aligned} L \times N^c &= K_\alpha \\ L \times V^c &= K_\alpha + H_{a\alpha} \end{aligned}$$

$$\begin{aligned} V \times V^c &= \eta + \pi_a + \phi_{ab} \\ L \times L^c &= \eta + \pi_a \end{aligned}$$

The chiral lagrangian describes the confined dynamics

$$\begin{aligned} \mathcal{L} \;=\; & \frac{f_\pi^2}{4}\text{Tr}[D_\mu U D^\mu U^\dagger] + (g_\rho f_\pi^3 \text{Tr}[MU] + h.c) \\ & - \frac{N}{16\pi^2 f_\pi} \sum_{G_1,G_2} g_{G_1} g_{G_2} \text{Tr}[\pi^a T^a F^{(G_1)} \tilde{F}^{(G_2)}] \\ & + \frac{3 g_2^2 g_\rho^2 f_\pi^4}{2(4\pi)^2} \sum_{i=1..3} \text{Tr}[U T^i U^\dagger T^i] \end{aligned}$$

Kinetic, mass and yukawa

Axial anomaly

Gauge contributions

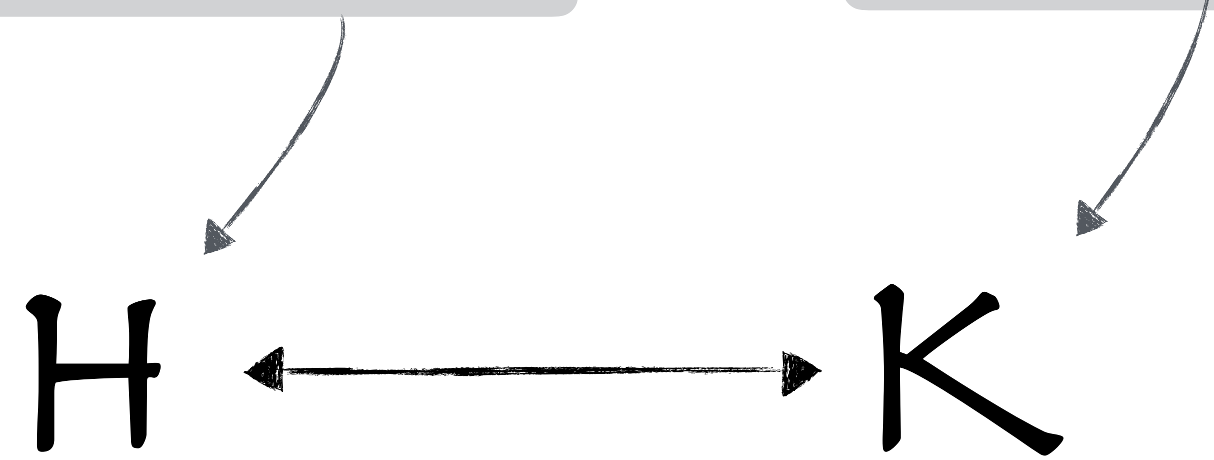
Theories of Vector-Like Confinement

From the mass term

$$y_\pm = (y \pm \tilde{y}^*)$$

$$\mathcal{L} \subset -m_K^2 |K|^2 - i y_- g_\rho f^2 (b K^\dagger H + h.c.) + y_+ g_\rho f \left(a_1 \eta K^\dagger H + a_3 \pi^a K^\dagger \sigma^a H + h.c. \right)$$

Mixing between the elementary Higgs and the composite Kaon



Before mass mixing only the SM elementary Higgs has coupling to SM matter

Half-Composite Type-I 2HDM [Antipin and Redi 1508.01112]

Theories of Vector-Like Confinement

From the anomaly term

$$\Gamma(\Pi \to VV) = c_\Pi^2 \frac{\alpha_i \alpha_j}{64\pi^3} \frac{m_\Pi^3}{f^2},$$

Anomaly coefficients:
depend on the reps of the VLFs

- Pions of identical species promptly decay through anomalies

$$\text{QCD} \quad \pi^0 \to \gamma\gamma \quad \text{vs.} \quad \pi^+ \to \ell^+ \nu \qquad \tau_{\pi^0} \ll \tau_{\pi^\pm}$$

From the point of view of the QED-QCD system this decay occurs through a non-renormalizable operator

Pions of different species can only decay through Yukawa terms

They are stable from the point of view of the strong sector

Technimeson Dark Matter [Antipin et al.1503.08749]

Indirect bounds on VLC theories

Higgs couplings

$$\mathscr{L} \supset |D_\mu H|^2 + |D_\mu K|^2 + \frac{c_K}{2f^2}(\partial_\mu |K|^2)^2 - \epsilon m_K^2 (K^\dagger H + h.c.) + y_u \bar{Q}_L \tilde{H} u_R + y_d \bar{Q}_L H d_R + y_e \bar{L}_L H e_R$$

Universal shift of Higgs couplings

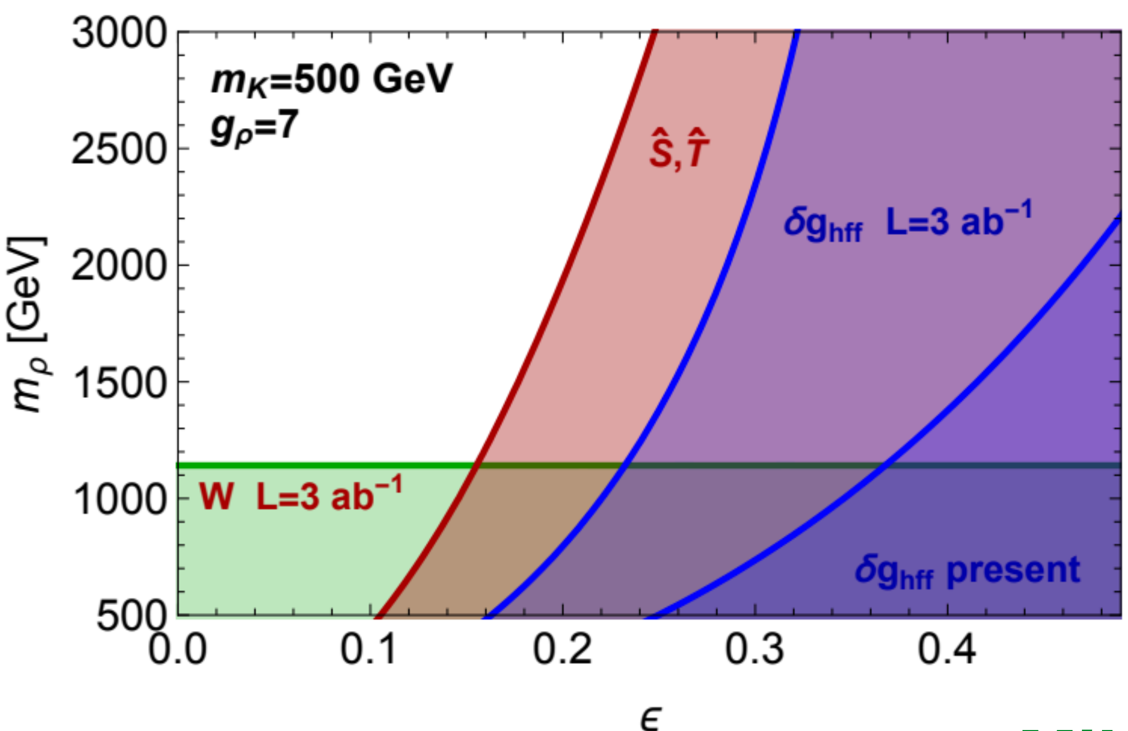
$$\frac{c_K |\epsilon|^4}{2f^2} O_H \qquad \frac{g_h}{g_h^{SM}}\bigg|_{\text{comp.}} = 1 - c_K |\epsilon|^4 \frac{v^2}{f^2},$$

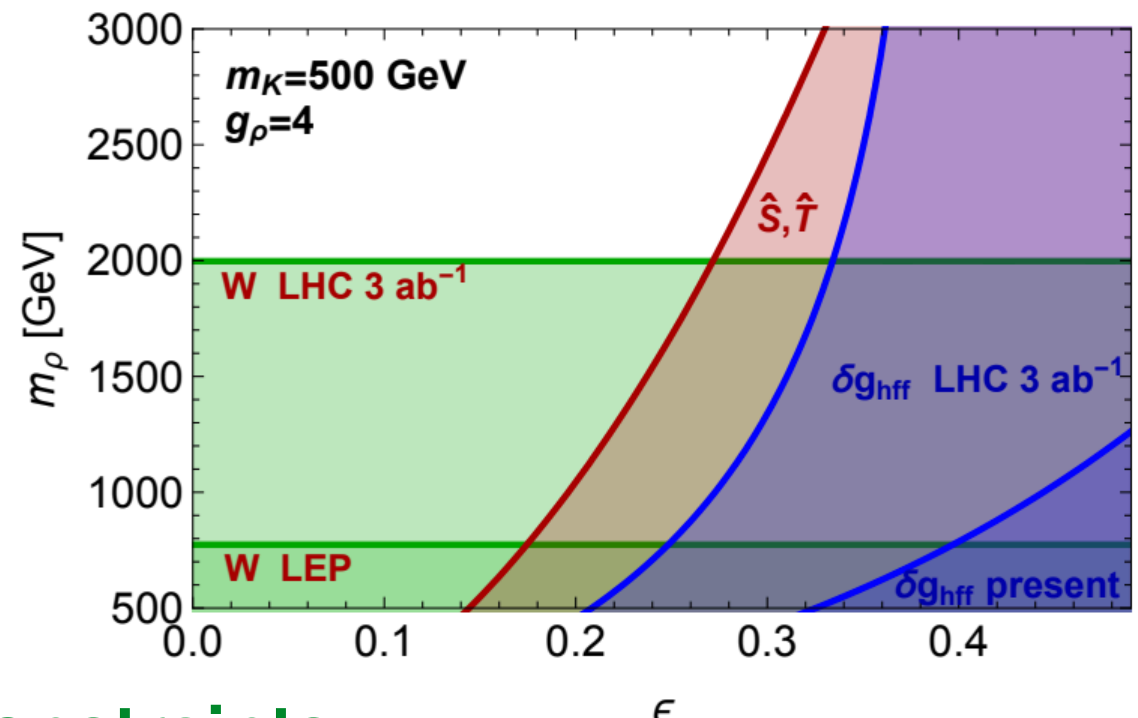
2HDM structure

$$\frac{\delta g_{hff}}{g_{hff}} = |\epsilon|^2 \frac{m_h^2}{m_K^2} \qquad \frac{\delta g_{hVV}}{g_{hVV}} = -|\epsilon|^2 \frac{m_h^4}{2m_K^4}$$

EWPO

$$\hat{T} \sim \epsilon^4 \frac{v^2}{f^2} \qquad \hat{S} \sim \epsilon^2 \frac{m_W^2}{m_\rho^2} \qquad W \sim \frac{m_W^2}{m_\rho^2}\frac{g_2^2}{g_\rho^2} = N \frac{\alpha_2}{4\pi}\frac{m_W^2}{m_\rho^2}$$





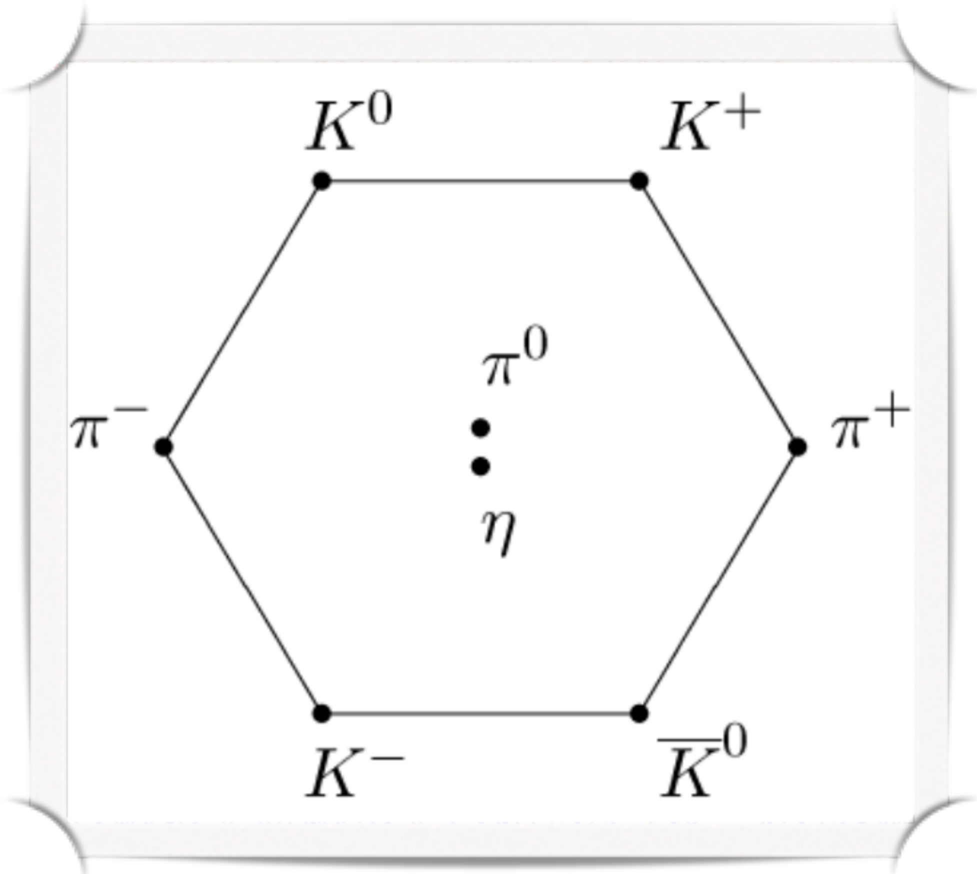
$\epsilon \sim \mathcal{O}(1) \times y_-$

Mild indirect constraints…

Collider Physics of VLC theories

Benchmark scenario: $L + N$ model

Three light flavours, chiral dynamics as in QCD - Easy to study



Techni-pions eightfold way

Tower of techni-rho present

η singlet - EW ALP like particle

K complex doublet mixing with the Higgs

π real triplet

Collider Physics of VLC theories

$y_+,\, y_- \sim 0$	$y_+,\, y_- \neq 0$
Anomalous scenario	Mixed scenario

Anomalous scenario

- K, π pair produced via EW interactions

$$\mathcal{L} \sim g W^a_\mu K^\dagger \sigma^a \overleftrightarrow{D} K$$

and through techni-rho decay $\rho \to \pi\pi$

- η, π decay through anomalies
- K stable

"Universal" phenomenology

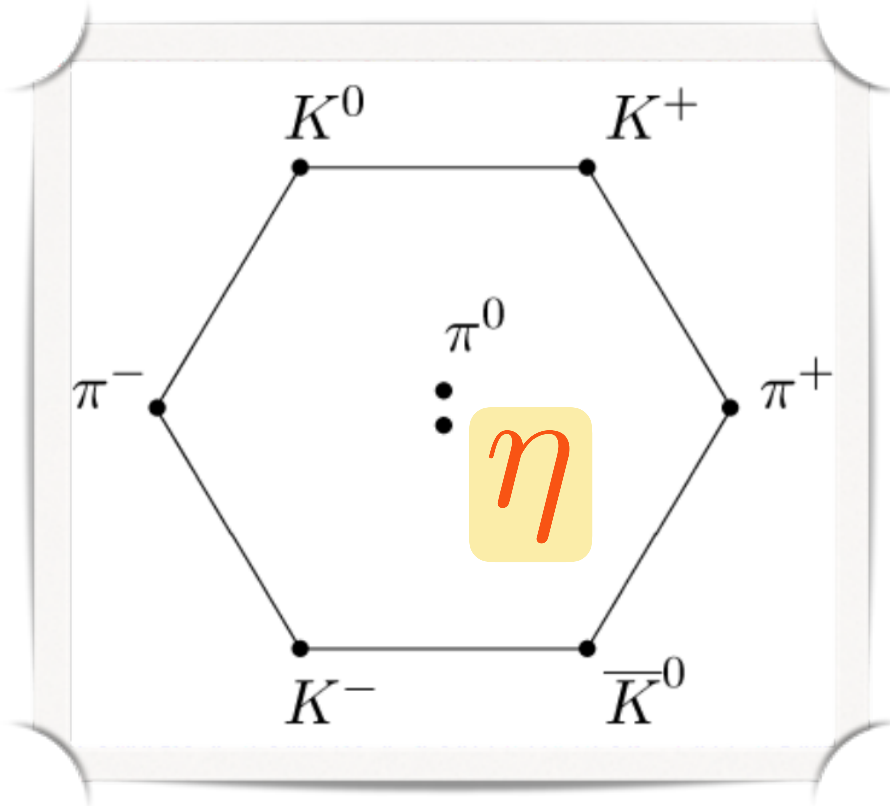
Mixed scenario

- K and H mix
- The Higgs VEV induces a mixing amongst all the pions
- Pions inherit also Higgs like decay

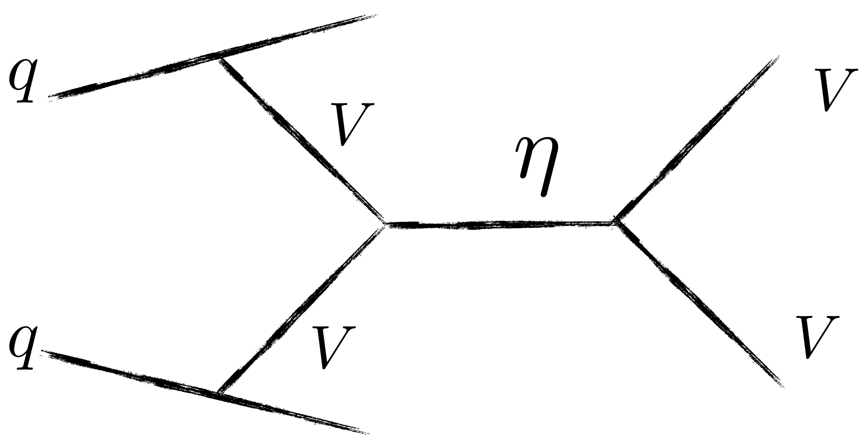
$y_+ \ll y_-$ or $y_+ \gg y_-$

Model dependent phenomenology

Collider Physics of VLC theories

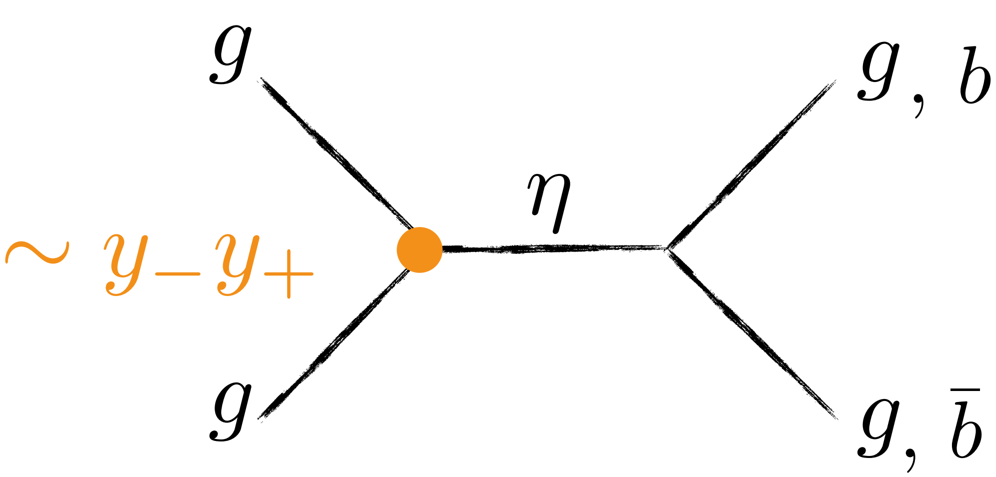


<u>Anomalous scenario</u>



Small production rates

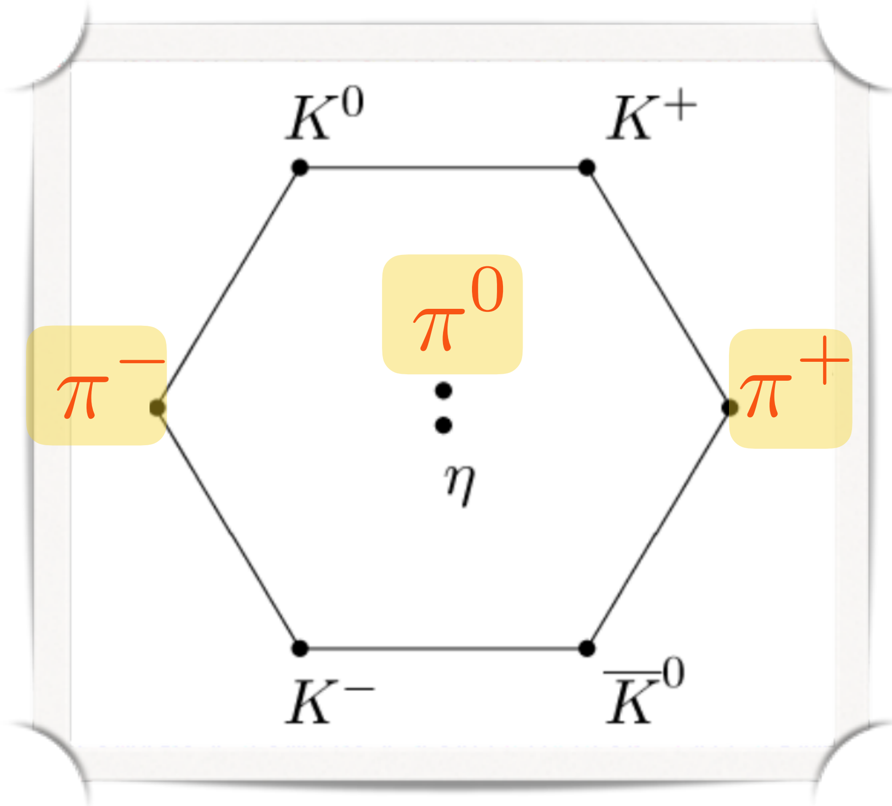
<u>Mixed scenario</u>



Large backgrounds

Elusive state: what can we say at the LHC for EW ALPs?

Collider Physics of VLC theories

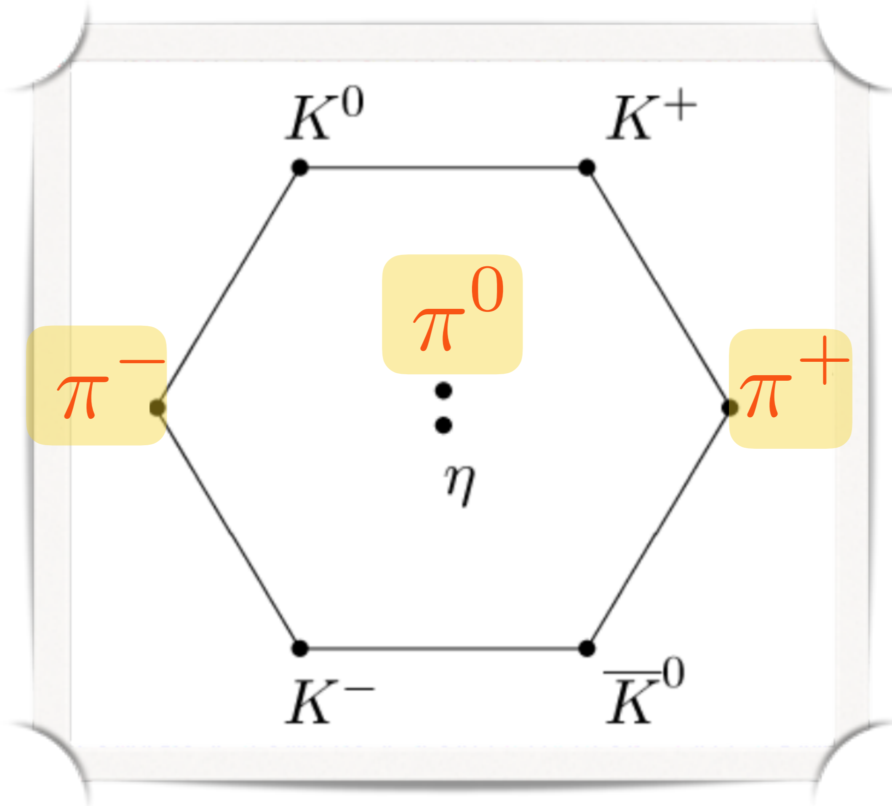


$$\mathcal{L} \sim \epsilon y_+ m_\rho \pi^a H^\dagger \sigma^a H$$

Mixed scenario:

- decay to longitudinal gauges bosons and fermions
- behaves as a Higgs-like states - production via gluon fusion
- possible to recast ZZ and WW resonances: $y_- y_+ < 0.1$

Collider Physics of VLC theories



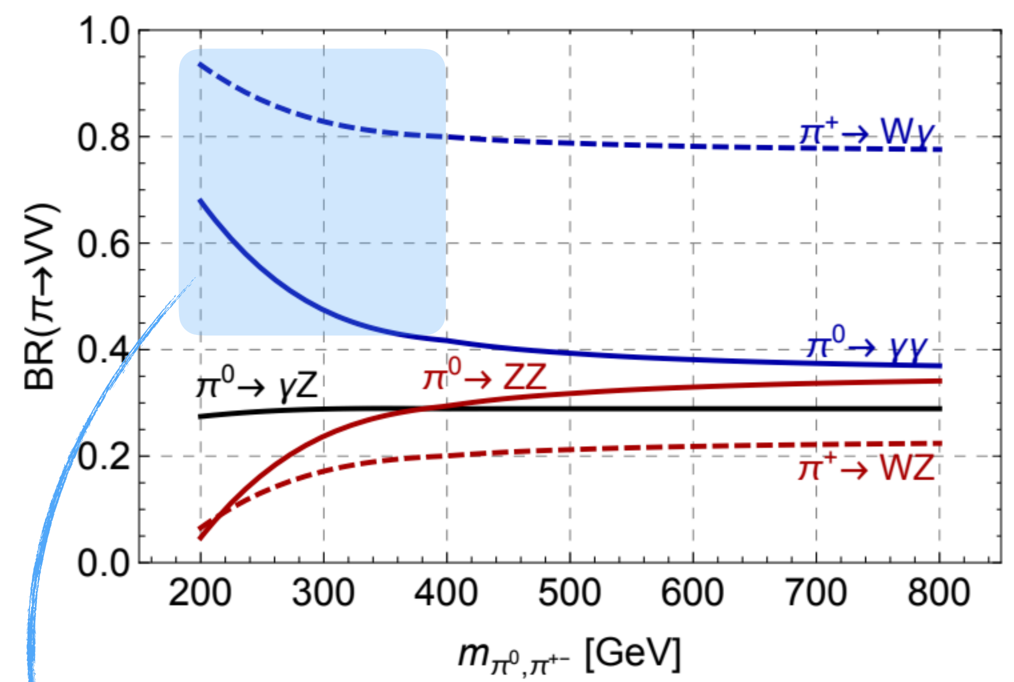
Anomalous scenario:

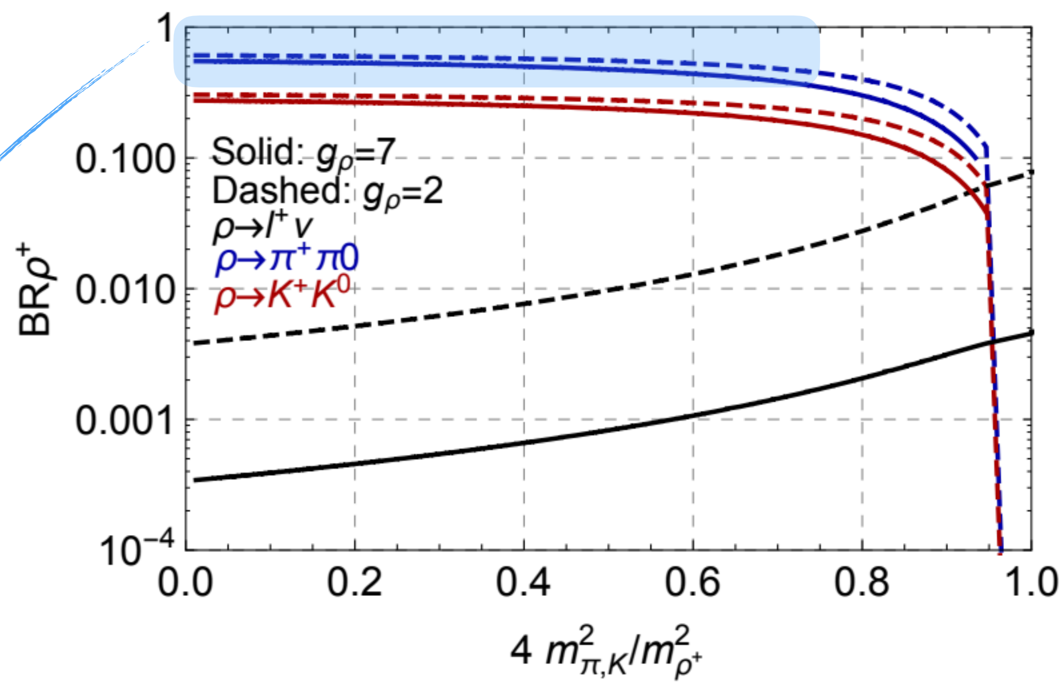
- pair production through s-channel SM gauge boson or techni-rho
  Single production through VBF generally subdominant
- decays in transverse gauge bosons
- sizable rates with clean final states!

Collider Physics of VLC theories

$$\mathscr{L}_{F\tilde{F}} = -c^{\pi}_{WB}\frac{g_1 g_2}{16\pi^2}\frac{\pi_a}{f}W^a_{\mu\nu}\tilde{B}^{\mu\nu}$$

$$\mathcal{L} \sim g_\rho \rho^\mu_a (\pi^T T^a \overleftrightarrow{D}_\mu \pi)$$



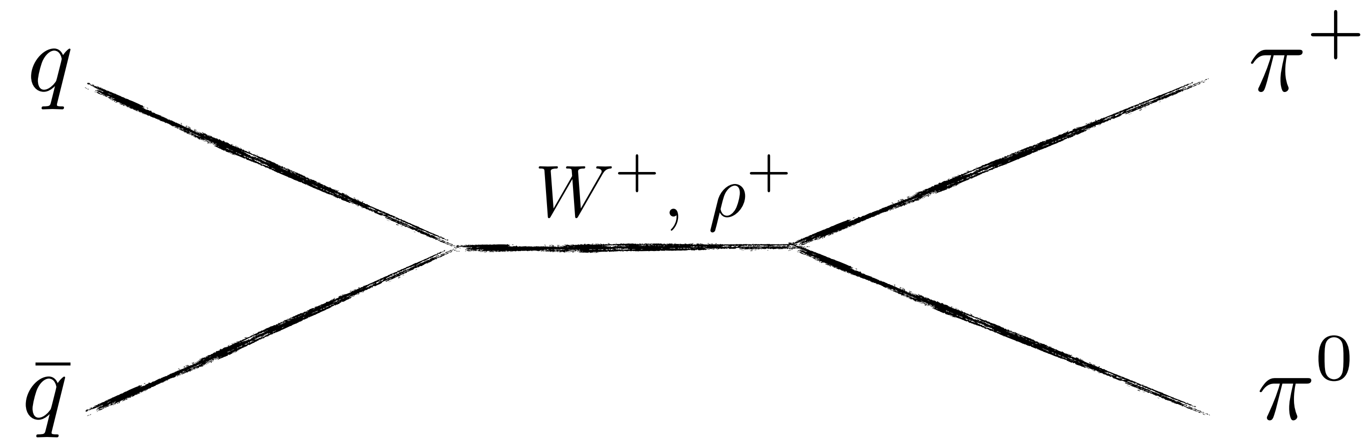


Decays with photons are the dominant ones

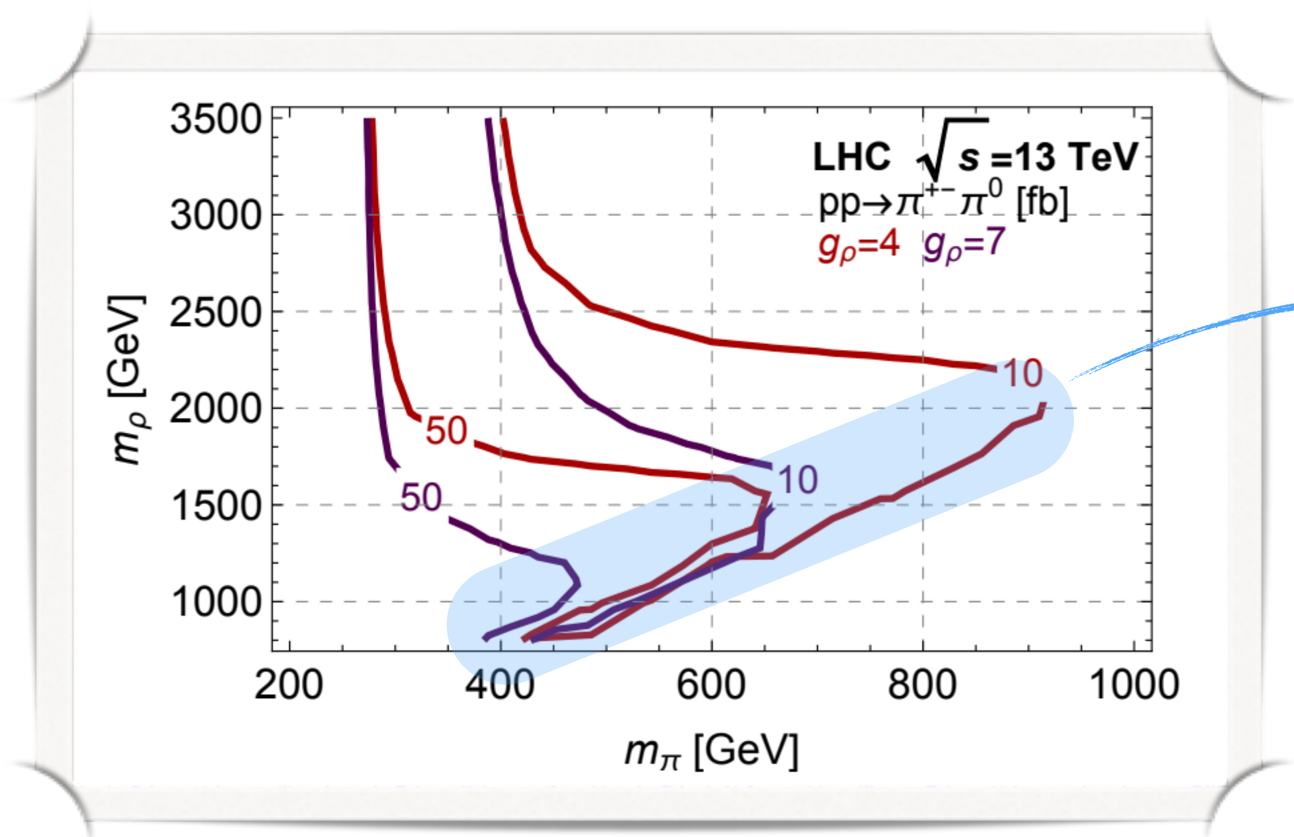
Almost 100% $\rho \to \pi\pi$ decay

Model available at http://feynrules.irmp.ucl.ac.be/wiki/VLC_LN

Collider Physics of VLC theories

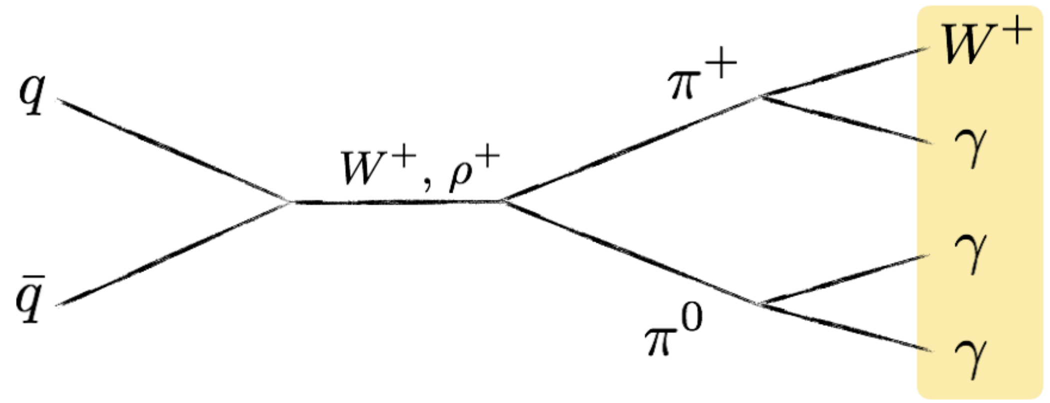


The exchange of a resonant techni-rho boosts the cross-section

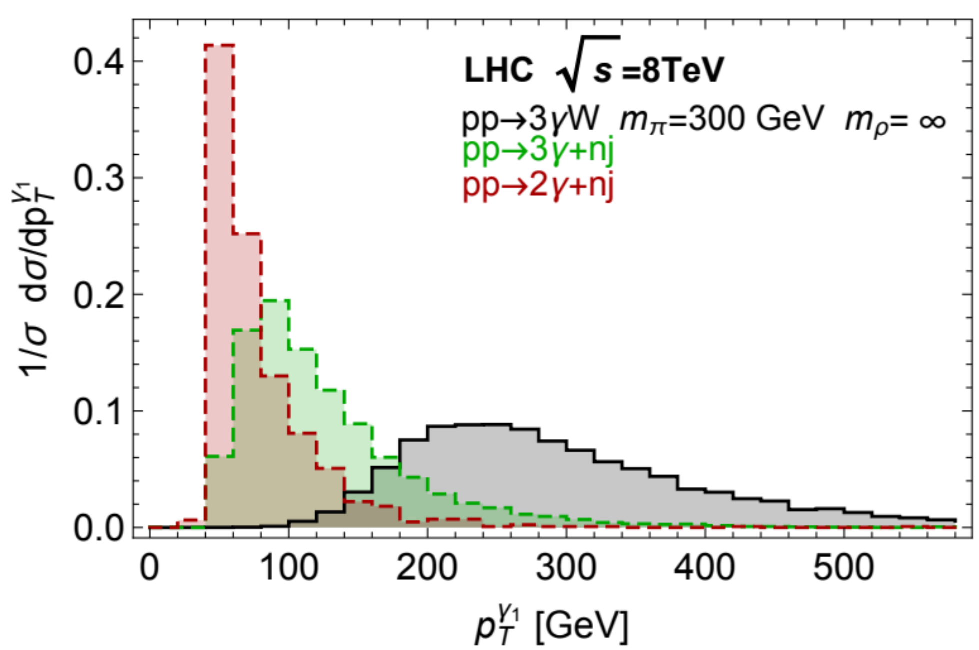


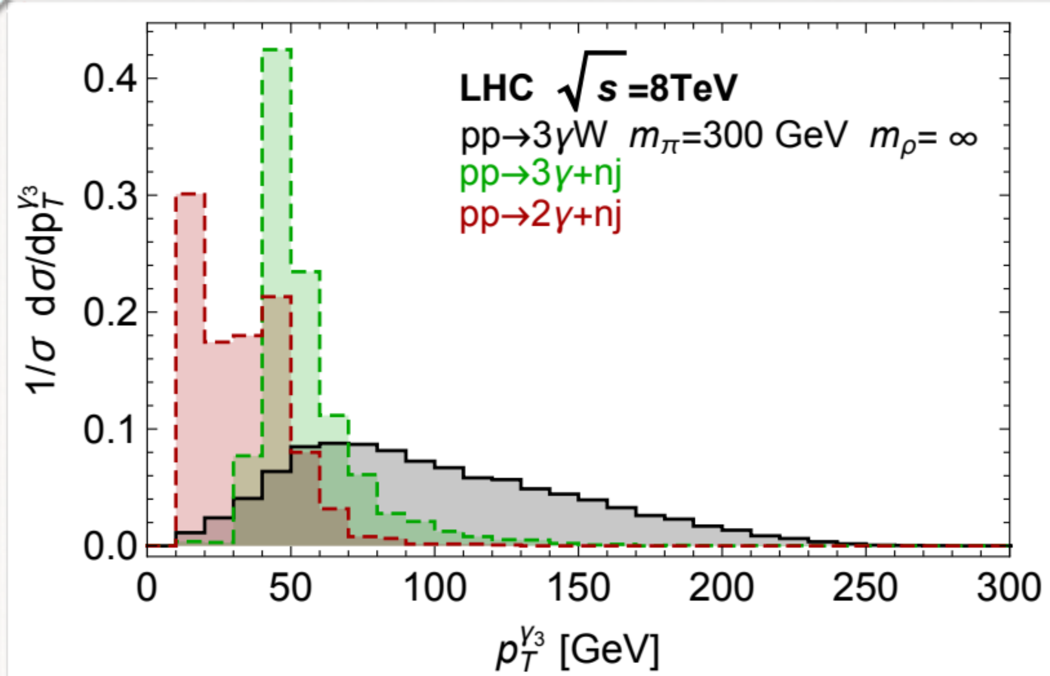
Resonant regime

Collider Physics of VLC theories



Clean $3\gamma W$ signature with $\mathcal{O}(10)\,\mathrm{fb}$ rates

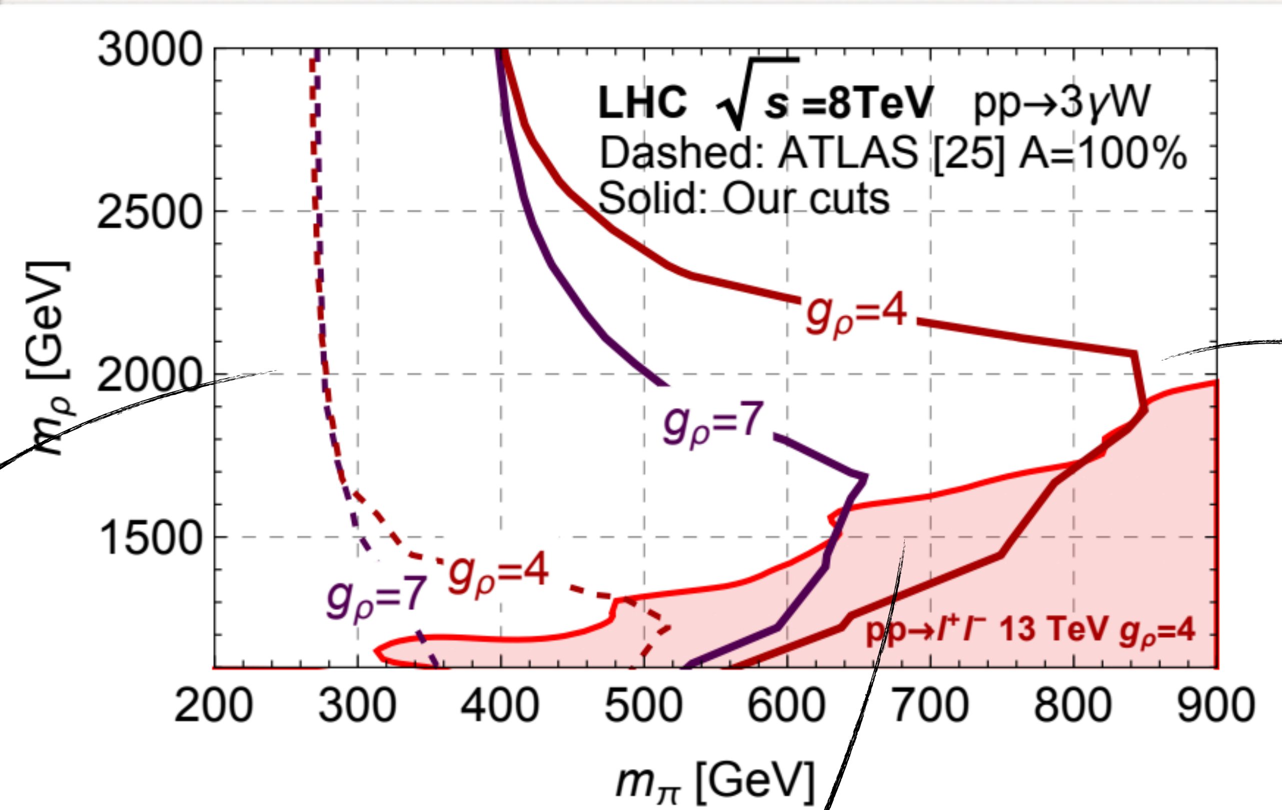




Hard photons allows to effectively reduce fake backgrounds from $2\gamma j$

Collider Physics of VLC theories

8 TeV

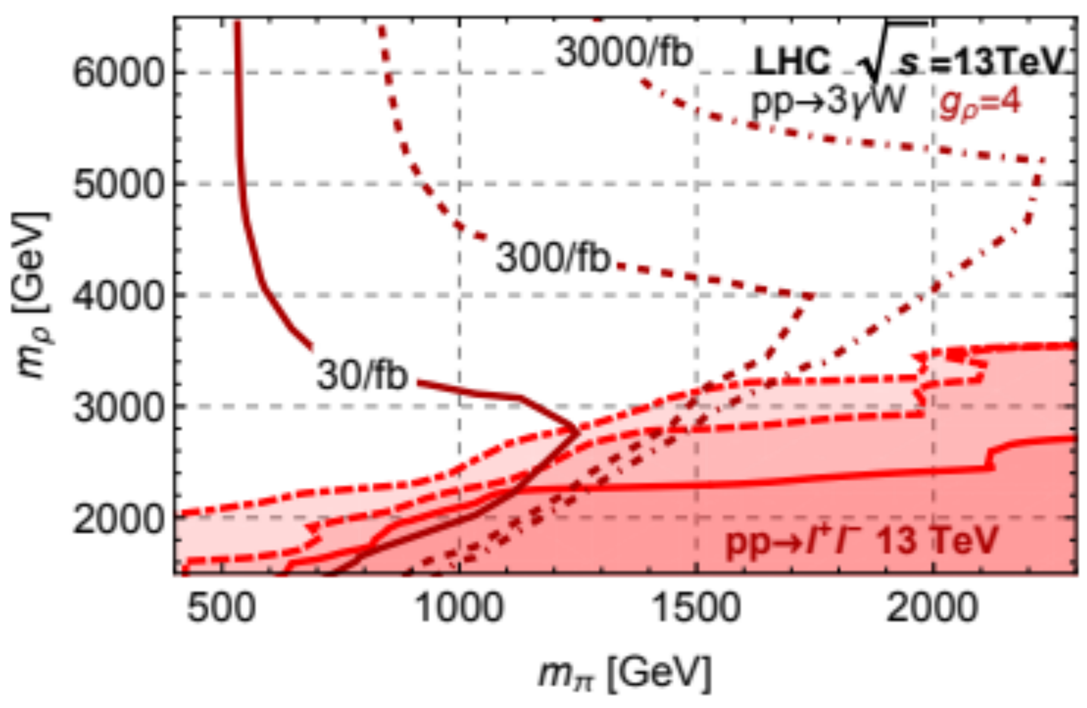


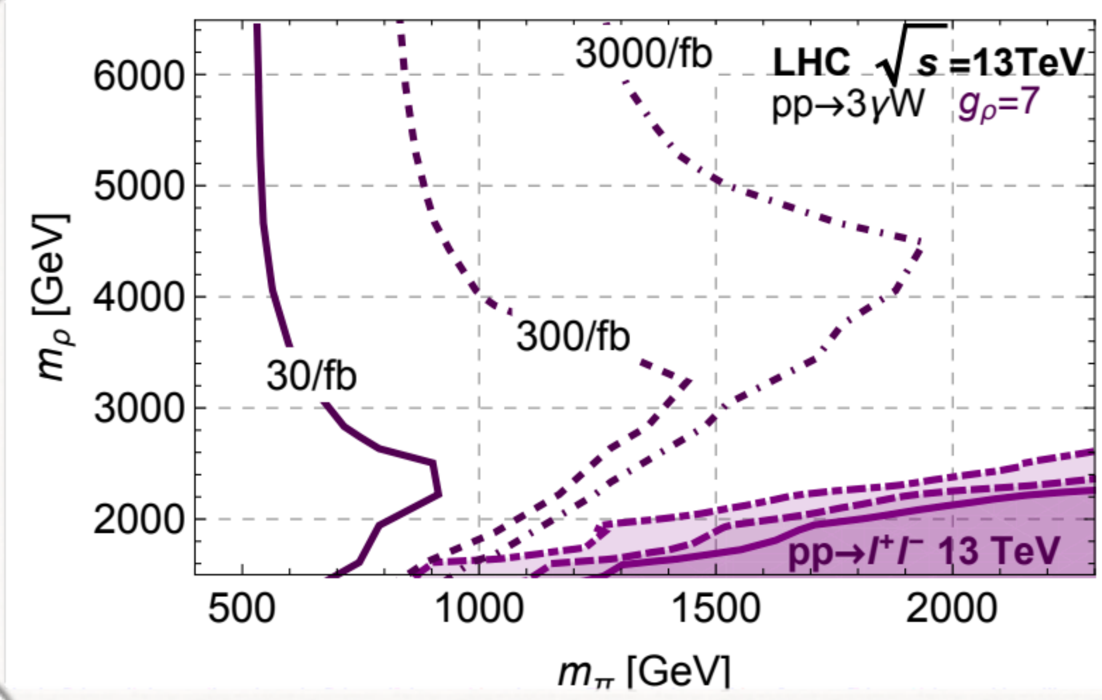
Bounds from current 3γ searches
$p_T^{\gamma_{1,2,3}} > 22,\ 22,\ 17\ \mathrm{GeV}$

Limits from optimized cuts
$p_T^{\gamma_{1,2,3}} > 250,\ 75,\ 75\ \mathrm{GeV}$

Complementarity with dilepton searches which loose sensitivity when the decay into pions is allowed - $g_\rho \gg g_{\mathrm{SM}}$

Collider Physics of VLC theories





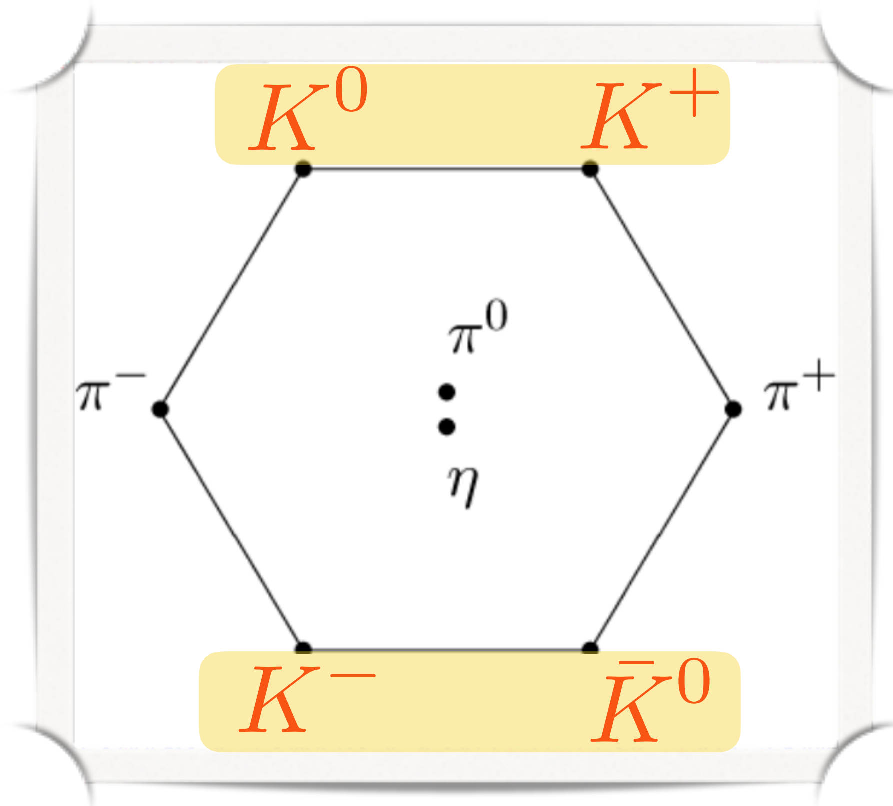
Simple selection cuts can improve the sensitivity up to ~ 1 TeV π masses

$$p_T^{\gamma_{1,2,3}} > 300,\ 100,\ 100\ \text{GeV}$$

No peak reconstruction required

The ATLAS collaboration is performing such analysis 😊

Collider Physics of VLC theories

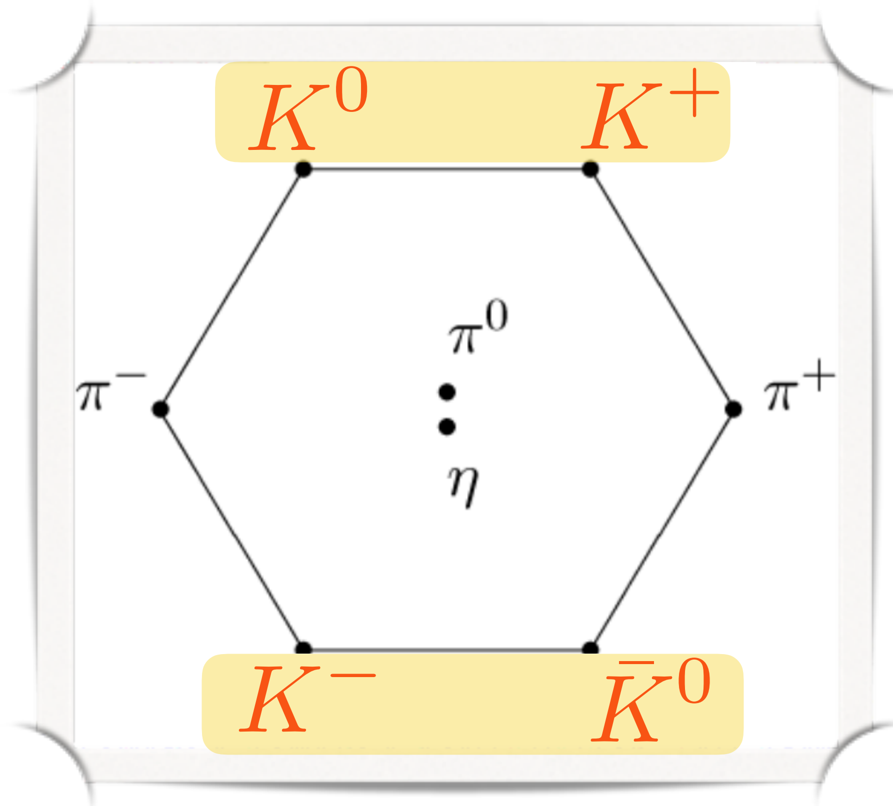


Anomalous scenario:

- stable due to species number conservation

- Signatures:
  - K^0 missing energy
  - $K^\pm$ charged track in the detector $m_K \gtrsim 400\,\mathrm{GeV}$

Collider Physics of VLC theories



Mixed scenario:

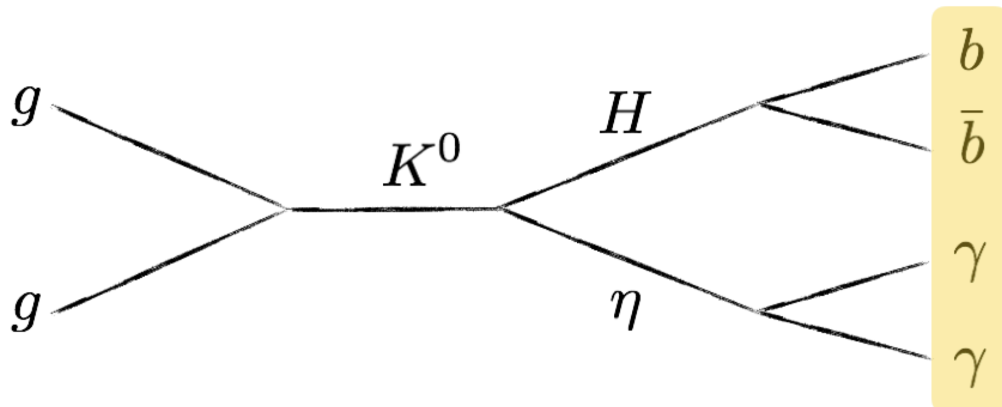
$$y_+ \ll y_-$$

- 2HDM type-I like structure: or give rise to different pheno

$$y_+ \gg y_-$$

Collider Physics of VLC theories

$$\frac{\Gamma(K^0 \to t\bar{t})}{\Gamma(K^0 \to H\eta)} \sim 36 \frac{y_-^2}{|y_+|^2} \frac{y_t^2}{g_\rho^2} \frac{m_\rho^2}{m_K^2}$$ if $y_+ \gg y_-$ $K^0 \to H\eta$ dominates

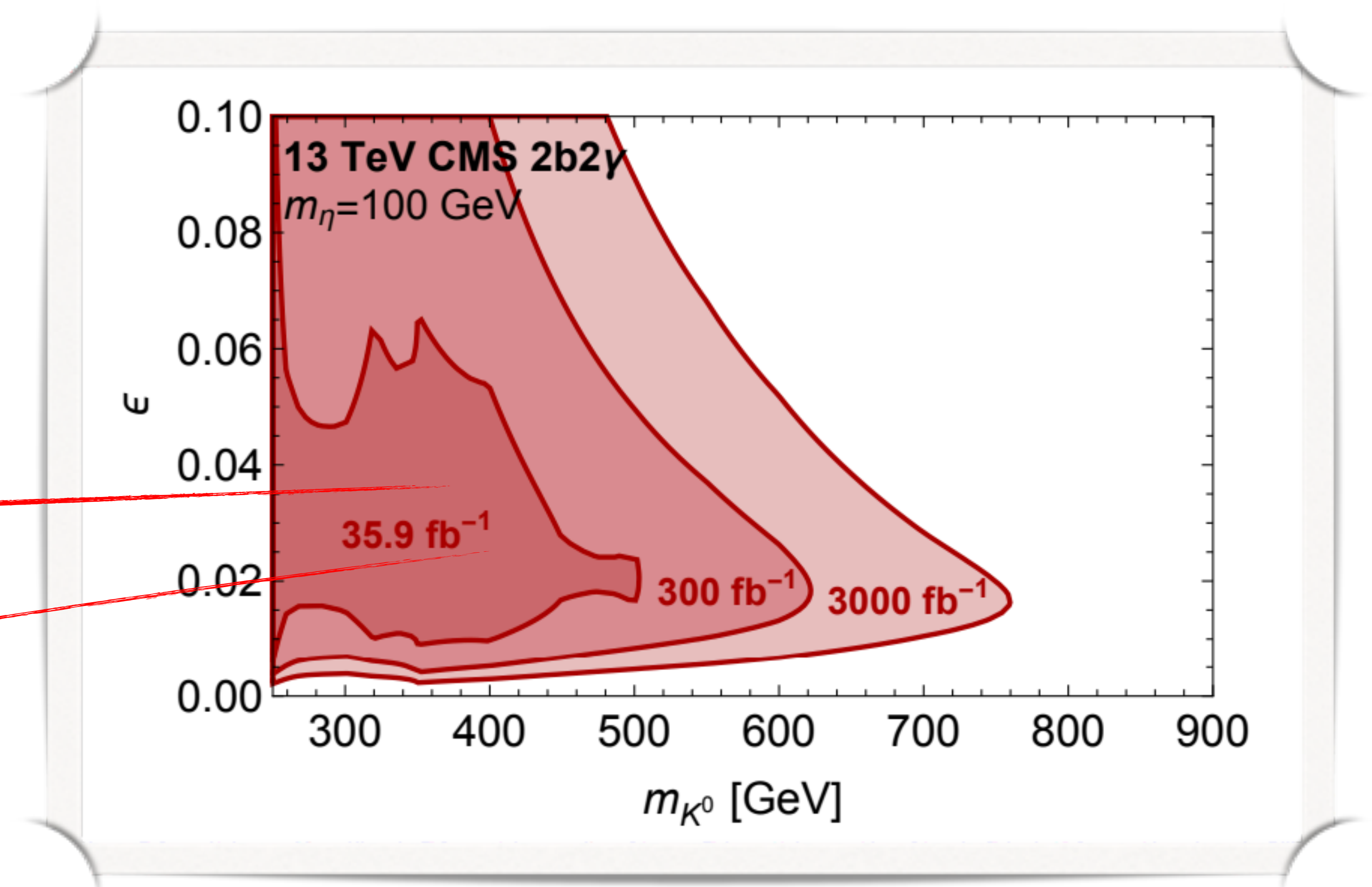


$2b2\gamma$ final state - HH production

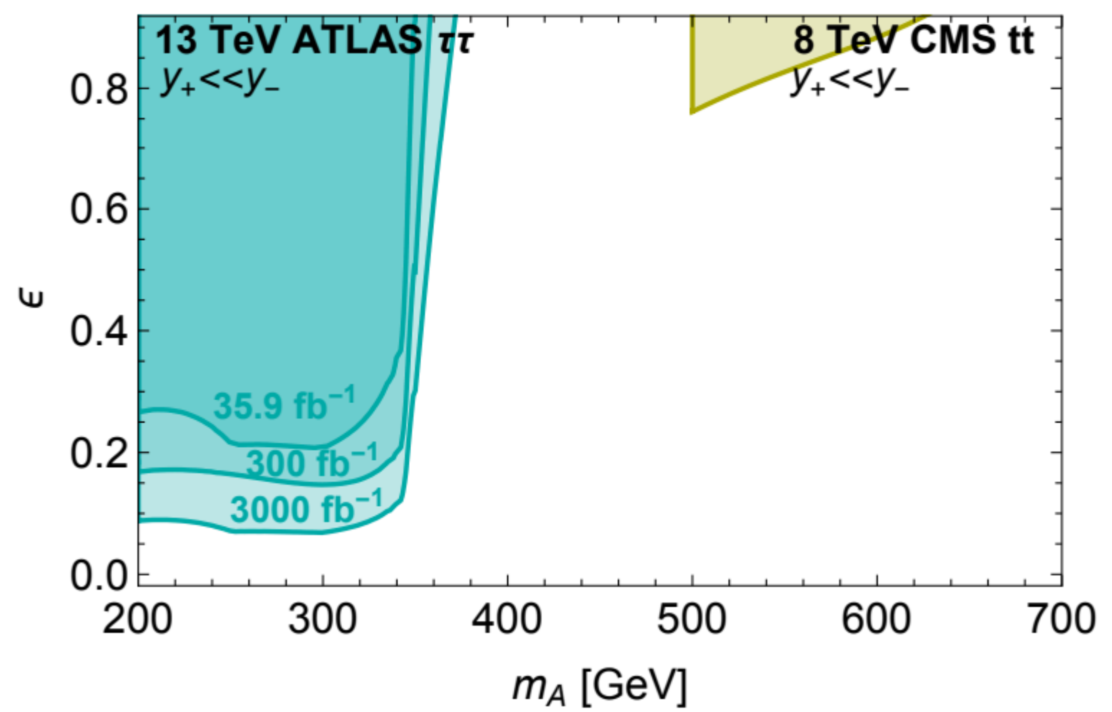
Gain $\frac{\mathrm{BR}(\eta \to 2\gamma)}{\mathrm{BR}(H \to 2\gamma)} \sim 10^3$ sensitivity

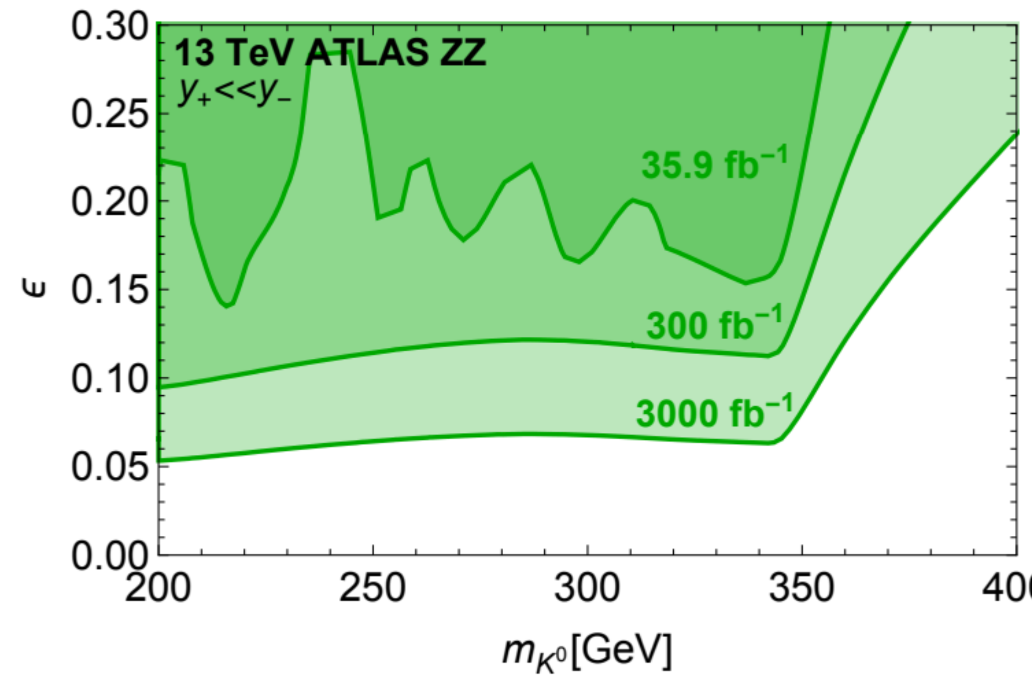
Probe also for η

Strong bound on the mixing angle



If $y_+ \ll y_-$ heavy-Higgs like behaviour





Heavy Higgs searches probe of this regime

Collider Physics of VLC theories

Models with a V-type VLQ presents quintuplet pNGBS

No mixing with the Higgs - simple phenomenology

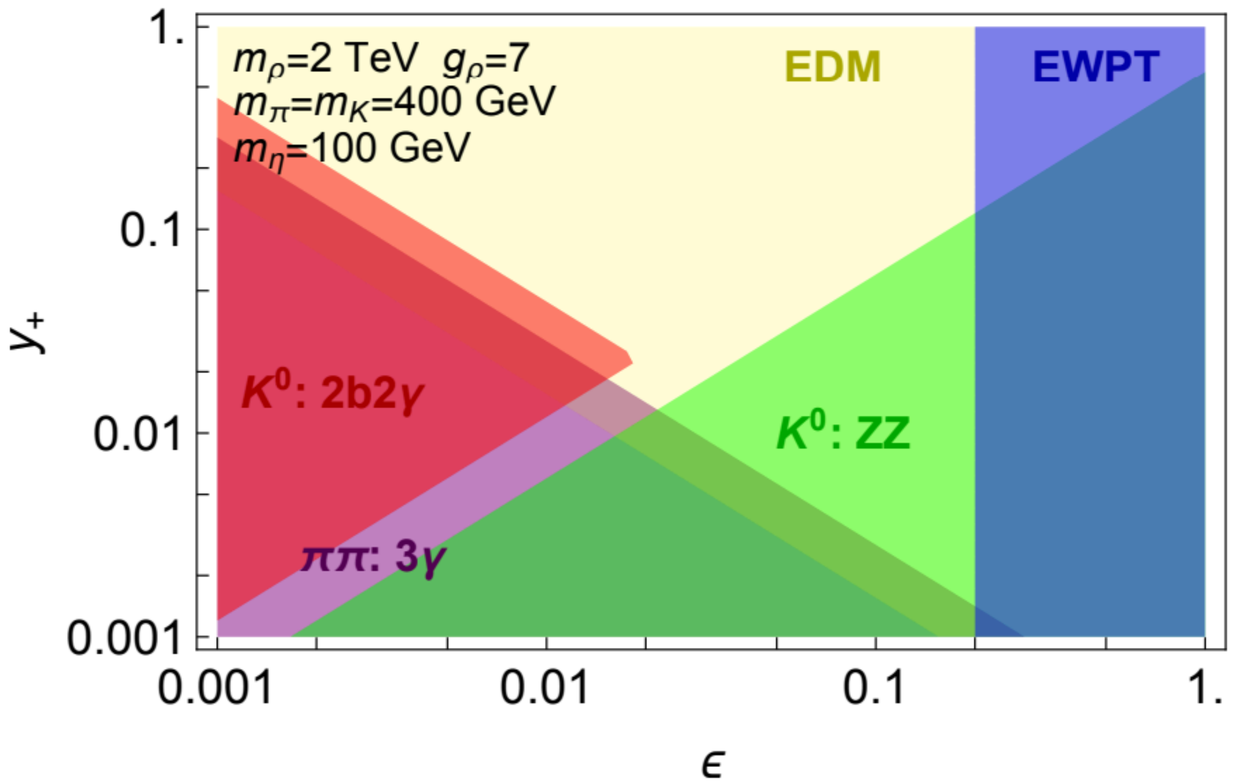
$$\sigma(pp \to \phi^{++}\phi^{--}) = 4 \times \sigma(pp \to \phi^{+}\phi^{-}) = 4 \times \sigma(pp \to \pi^{+}\pi^{-}) \,,$$
$$\sigma(pp \to \phi^{\pm\pm}\phi^{\mp}) = \frac{2}{3} \times \sigma(pp \to \phi^{\pm}\phi^{0}) = 2 \times \sigma(pp \to \pi^{\pm}\pi^{0}) \,.$$

$4W$ final state - same-sign multilepton $m_{\phi}^{++} \gtrsim 400\,\mathrm{GeV}$

$3\gamma W$ as for the pions - with higher cross-section

LHC Pheno Summary

$$d_e \sim 10^{-26}\,\mathrm{e\,cm} \times \mathrm{Im}[y_- y_+^*] \times \left(\frac{\mathrm{TeV}}{\mathrm{Min}[m_{\pi_3,\eta}]}\right)^4 \times \left(\frac{m_\rho}{\mathrm{TeV}}\right)^2$$



Anomalous scenario

NGB	Production	Decay	Model parameters	LHC
π	EW pair prod.	multi-V_T	$c_{VV} N/f_\pi$	✓
K	EW pair prod.	disappearing tracks/HSCP/E_T^{miss}	–	✓

Tree-level scenario $y_- \gg y_+$

NGB	Production	Decay	Model parameters	LHC
π	gg-fusion	$V_L V_L$	ϵy_+	✓
K	gg-fusion	$V_L V_L$	ϵ	✓
η	gg-fusion	$V_T V_T, tt, bb$	ϵy_+	

$P-$invariant scenario $y_+ \gg y_-$

NGB	Production	Decay	Model parameters	LHC
π	gg-fusion	$V_L V_L$	ϵy_+	✓
K	gg-fusion	$H\eta$	ϵ	✓
η	gg-fusion / K decay	$V_T V_T, tt, bb$	ϵy_+	✓

- VLC theories are safe from EWPT and flavour bounds
- Rich phenomenology testable in multiple final states
- Signatures common to many models for composite Dark Matter
- Experimental efforts are being pursued

What else?

For $SU(N)$ NP with N-odd $\mathcal{B} \sim \epsilon_{i_1 i_2 i_N} \psi_1 \psi_2 \psi_N$ is a fermion

For $SU(N)$ NP with N-odd $\mathcal{B} \sim \epsilon_{i_1 i_2 i_N} \psi_1 \psi_2 \psi_N$ is a fermion

Lightest state expected to have spin 1/2

States with the quantum number of a right-handed neutrino

$$\mathcal{L}_{IR} \sim \frac{1}{\Lambda_1^3} L \tilde{H} [\psi\psi\psi] + \frac{1}{\Lambda_2^5} [\psi\psi\psi][\psi\psi\psi] + \frac{1}{\Lambda_3^5} [\bar{\psi}\bar{\psi}\bar{\psi}][\psi\psi\psi] + \dots$$

$$\downarrow$$

$$\mathcal{L}_{IR} \sim \frac{\mu^3}{\Lambda_1^3} L \tilde{H} B_R + \frac{\mu^6}{\Lambda_2^5} (B_R B_L + L \leftrightarrow R) + \frac{\mu^6}{\Lambda_3^5} (\bar{B}_L B_R + R \leftrightarrow L) + \dots$$

Need to break the accidental technibaryon symmetry to allow for the mixing

Without further protections this triggers the decay of the DM technibaryon

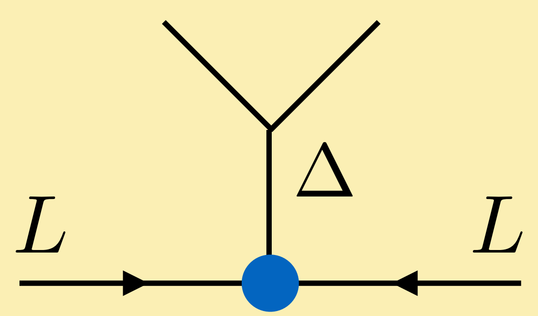
Q: Possible to reconcile $\tau_{\rm DM} > 10^{17}\ {\rm s}$, $m_\nu \sim {\rm eV}$ **?**

Another possibility is to use a technimeson instead than a technibaryon

Models with a technimeson with (1,3,1) quantum number under GSM exist

Is it possible to realize the Weinberg operator via a ~ type II see-saw

$$\mathcal{L} \sim \bar{L}^c \epsilon \, \Delta \, L$$

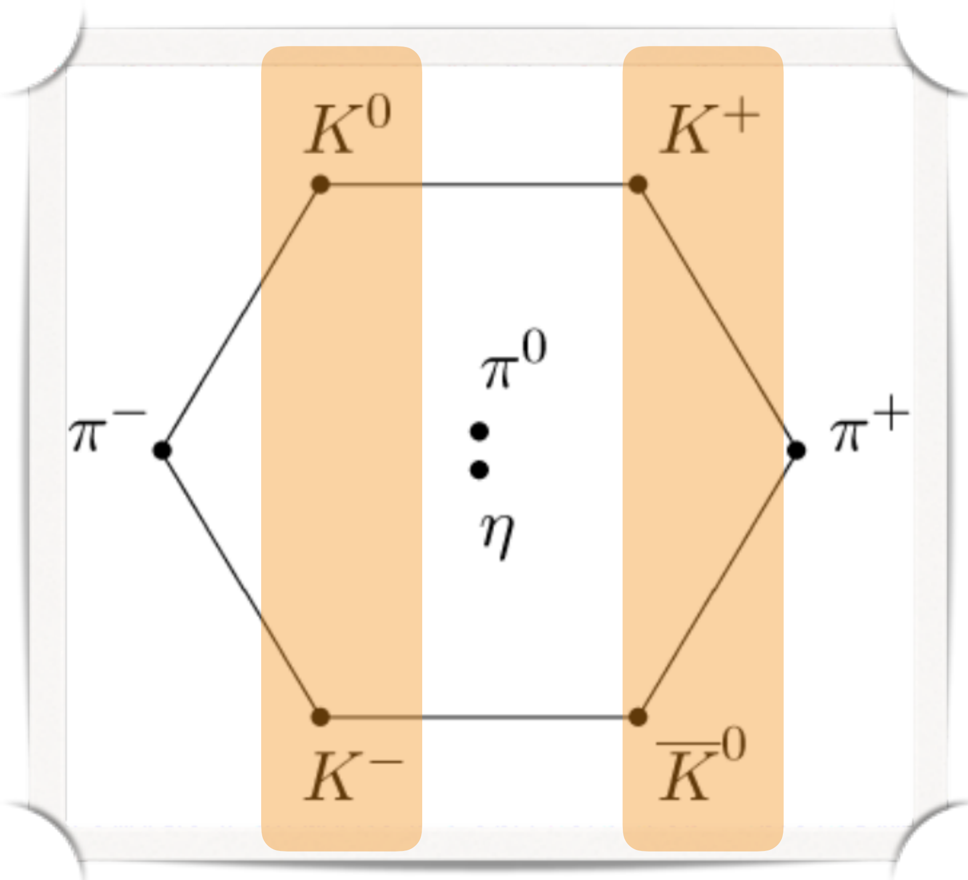


Δ is $\bar{\psi}\psi$ to generate the interaction no need to break the accidental U(1)

In principle possible to reconcile DM and neutrino masses

Consider $SU(3)$ NP theories with L + N quantum numers

Higgs doublet quantum numbers



QCD-like dynamics: easy to study

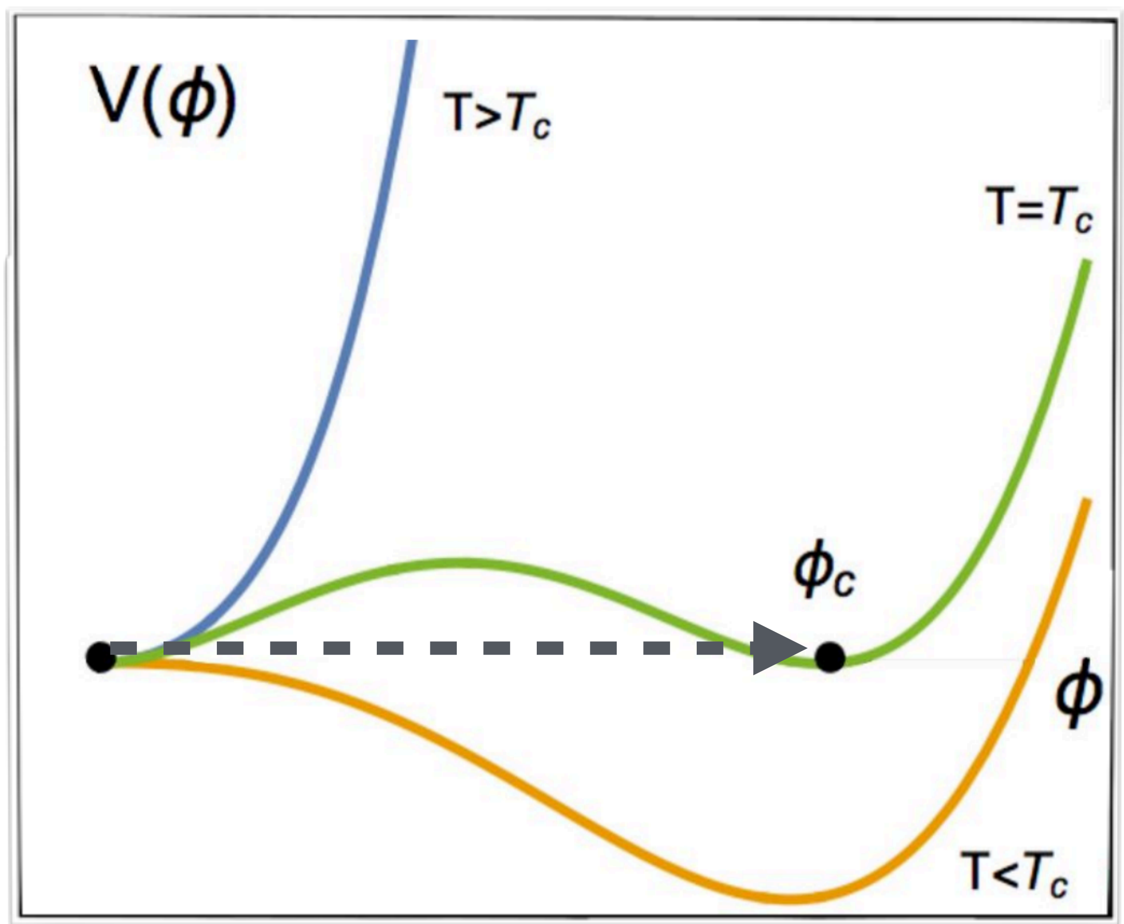
From the expansion of the chiral Lagrangian

$$\mathcal{L}_{CPT} \sim \lambda H^{\dagger} \tilde{K} \tilde{\eta}^2 \longrightarrow \lambda s_\beta |H|^2 \tilde{\eta}^2$$

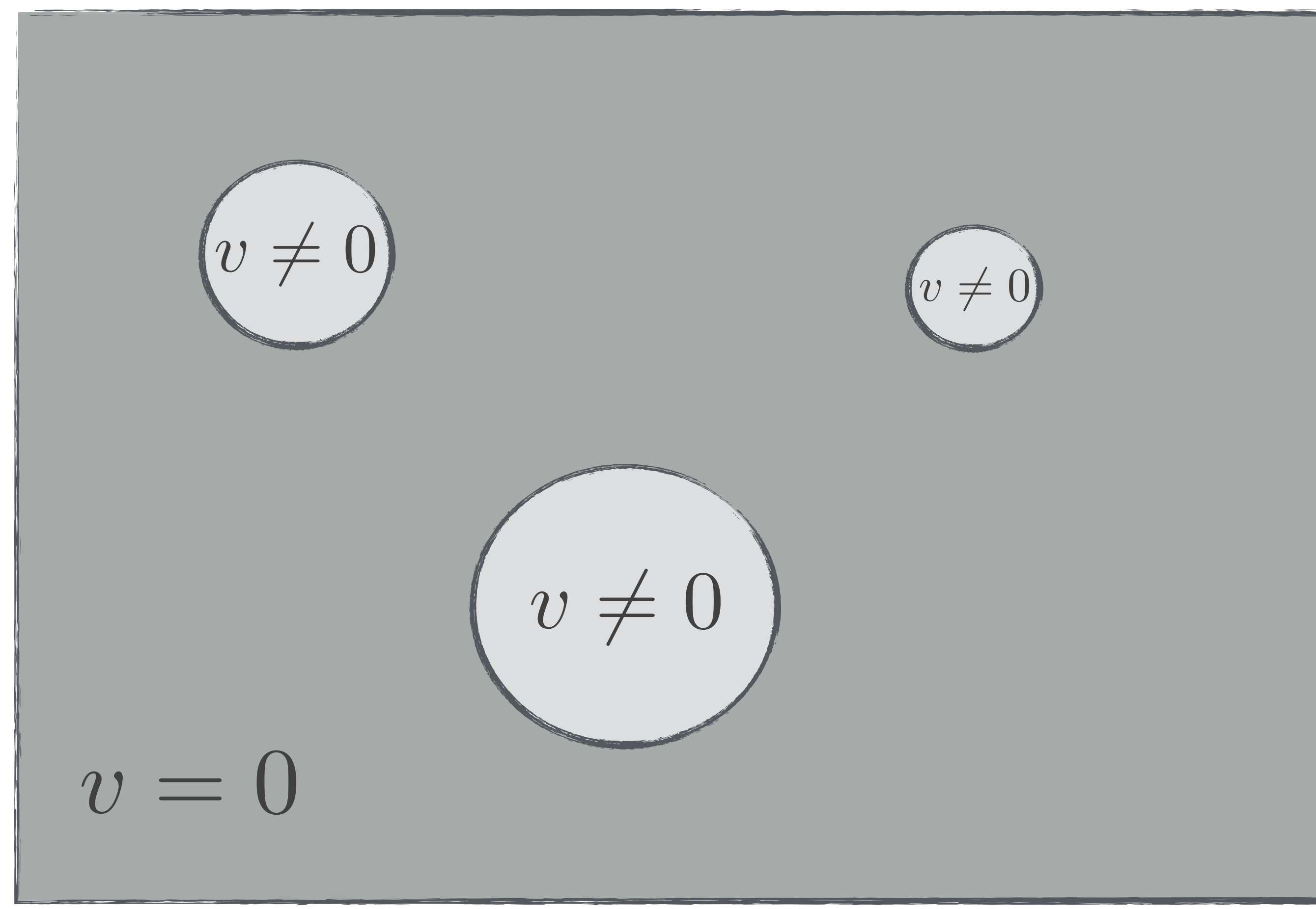
$$V \sim m^2(T)|H|^2 - \frac{(\lambda s_\beta)^{3/2} T}{12\pi} |H|^3 + \lambda |H|^4$$

Induces temperature dependent cubic term in the Higgs potential

$$v_c/T_c \sim v^2/m_h^2 \, \lambda \, \sin\beta$$



True vacuum via bubbles nucleation



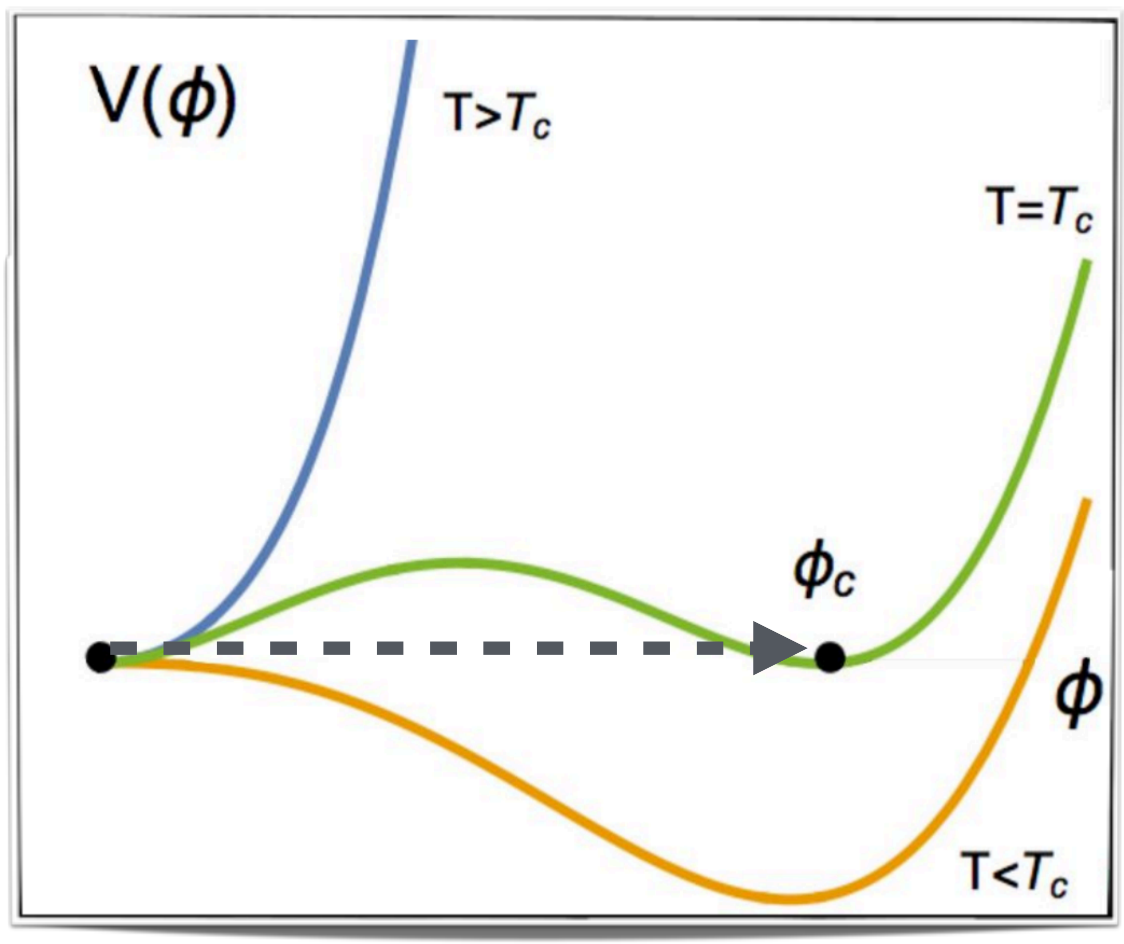
From the expansion of the chiral Lagrangian

$$\mathcal{L}_{CPT} \sim \lambda H^{+} \tilde{K} \tilde{\eta}^2 \longrightarrow \lambda s_\beta |H|^2 \tilde{\eta}^2$$

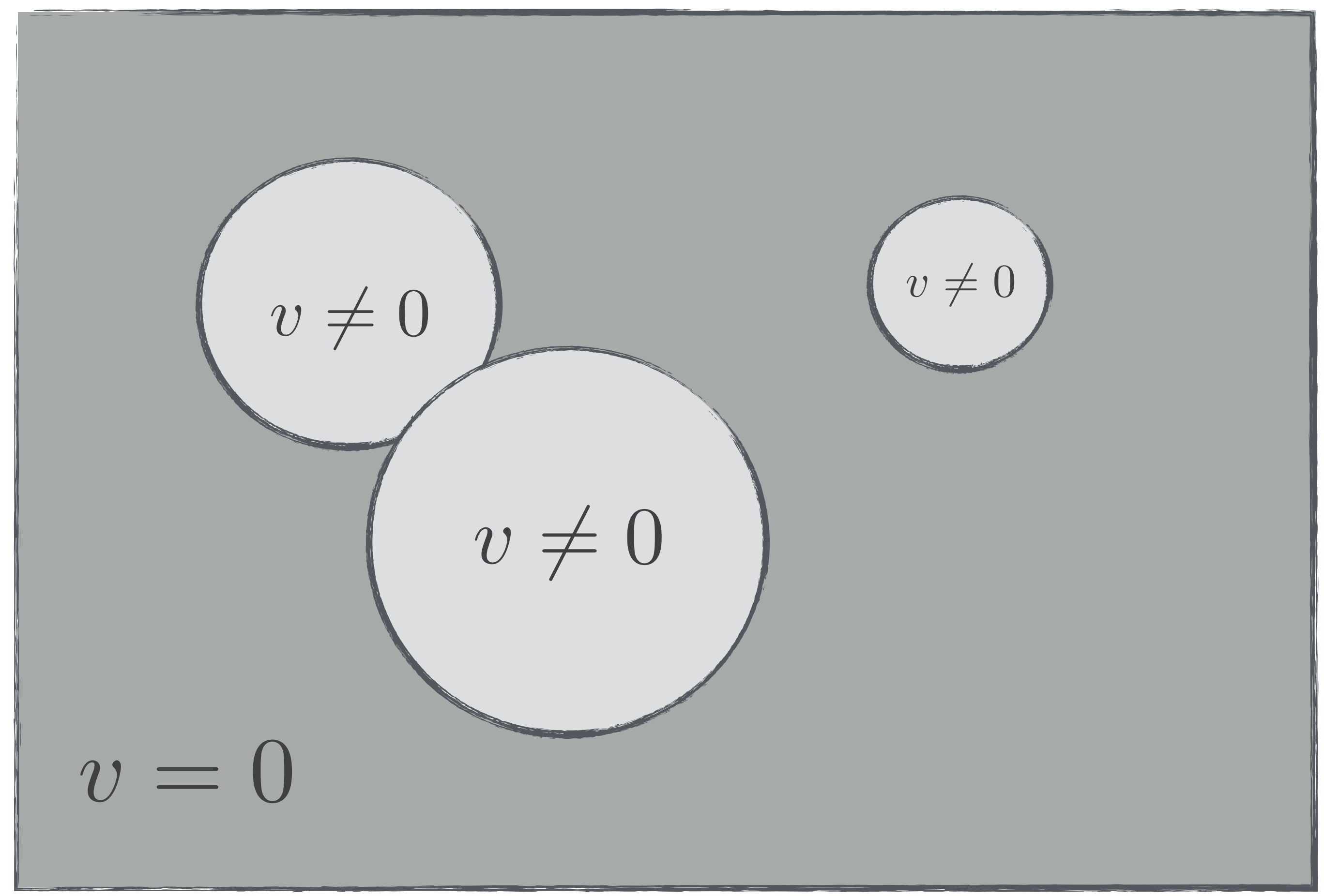
$$V \sim m^2(T)|H|^2 - \frac{(\lambda s_\beta)^{3/2} T}{12\pi} |H|^3 + \lambda |H|^4$$

Induces temperature dependent cubic term in the Higgs potential

$$v_c/T_c \sim v^2/m_h^2 \, \lambda \, \sin\beta$$



True vacuum via bubbles nucleation



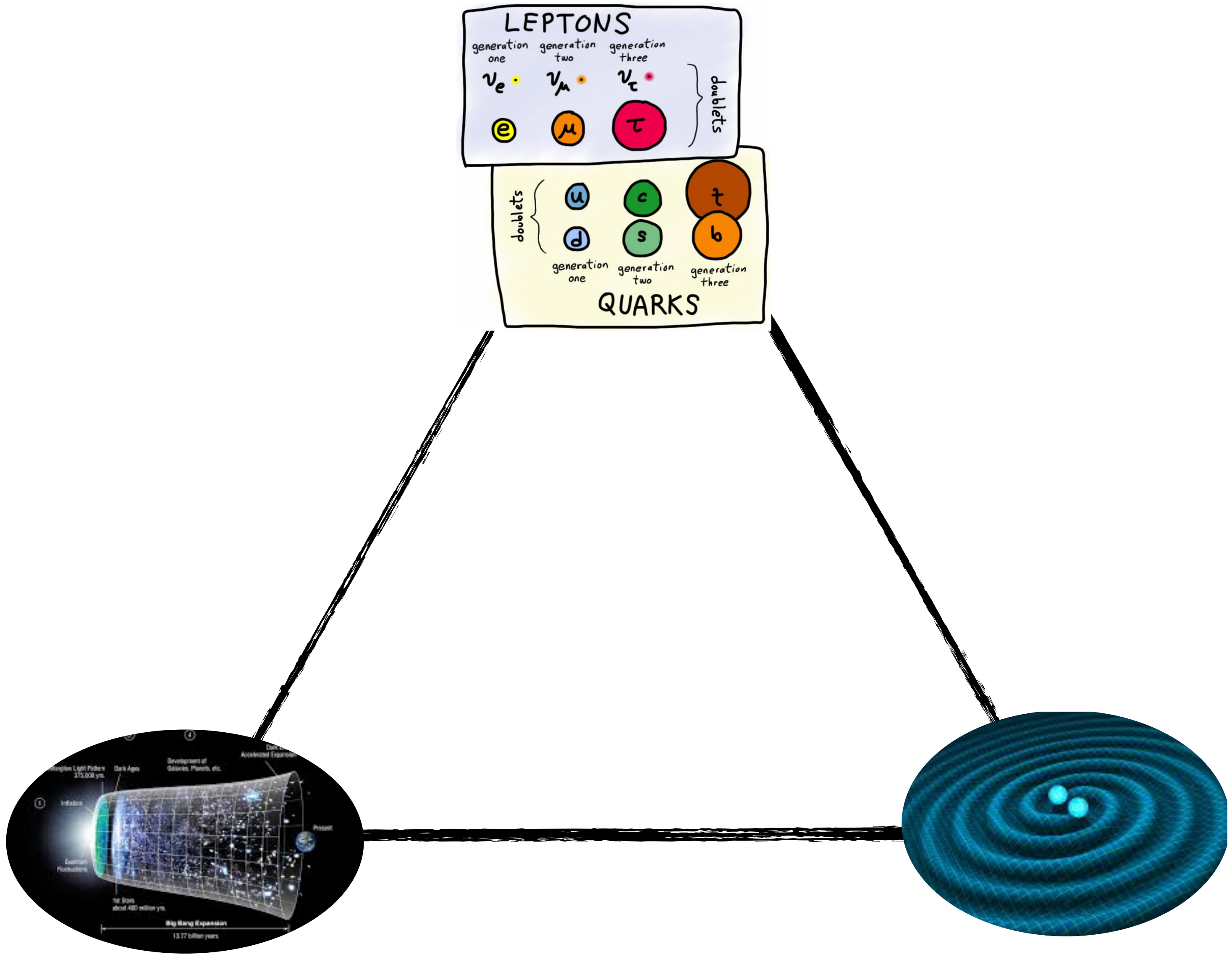
Bubble collision with $T_c \sim 100$ GeV produces GW with frequencies 10 mHz

In the range of GW interferometers!

The Standard Model (+ $\Delta\mathrm{SM}$)

Elementary particle physics

LHC, Belle-II, T2K, Icecube…



$\Lambda\mathrm{CDM}$ model

Cosmology

Planck, FermiLAT…

General relativity

Gravity

Ligo, Virgo…

Multiphoton background

Comparison with ATLAS [25]

Process	[25] [fb]	Our [fb]
3γ	16.7	18.4
2γ j	17.2	83.4

Comparison with [44]

Process	[44] Gen. [fb]	Our Gen. [fb]	[44] Reco. [fb]	Our Reco. [fb]
$3\gamma + \{0,1,2\}j$	2.5	3.7	2.0	1.6
$2\gamma + \{0,1,2\}j$	7.2×10^3	9.7×10^3	5.9	4.7

$\gamma - j$ Mis-ID probability

$$\mathcal{P}_{j\to\gamma} = \begin{cases} 9.5\times10^{-4} + 1.5\times10^{-4}\times p_T/\mathrm{GeV} & p_T < 28\ \mathrm{GeV} \\ 0.0093 e^{-0.036 p_T^j/\mathrm{GeV}} & p_T > 28\ \mathrm{GeV} \end{cases}$$